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SUPPLEMENTAL REPORT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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EVALUATION OF VELOCITY ERROR
IN IMU DURING ASCENT PHASE
(GEMINI 2 and GEMINI 3 MISSIONS)

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Gemini 3
by: Gemini 3 Mission Evaluation Team
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

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EVALUATION OF VELOCITY ERROR IN IMU DURING ASCENT PHASE (GEMINI 2 and GEMINI 3 MISSIONS)

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DOWNGRADED AT 3-YEAR INTERVALS,
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Gemini 3
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Attention: Gemini Program Office, Phyllis T. Jenness, (GA)

Subject: Contract NAS 9-170, Project Gemini, Transmittal of Data

Reference: (a) NASA TWX GT 11032, Received 13 May 1965

Enclosures: (1) MAC Report B984, GT-2 and GT-3 IGS Ascent Anomaly Investigations - Reproducible
(2) MAC Report B984, GT-2and GT-3 IGS Ascent Anomaly Investigations

1. In compliance with item "A" of Reference (a), Enclosure (1) is hereby transmitted.

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ABSTRACT

IGS velocity errors were experienced during the ascent portions of the GT-2 and GT-3 missions. Extensive data evaluations and hardware tests were performed after each flight. The cause or causes of each of the anomalies were isolated and corrective action instituted prior to the succeeding Gemini launch.

1.0 Summary.-

1.1 GT-2 Comments.- The Gemini IGS, flight tested in S/C #2 on 19 January 1965, experienced an apparent velocity error in the down range (X) accelerometer loop. The velocity increase occurred in large steps over several seconds at linear acceleration levels above 4.4 g's. Post flight evaluations revealed that the anomaly was caused by a pulse lock-up phenomenon in the accelerometer pulse rebalance loop. Corrective action has been taken on future units to ensure that this error does not recur. The accelerometer loop rate network has been modified to remove the possibility of a pulse lock-up.

1.2 GT-3 Comments.- Evaluation of the S/C #3 flight data revealed errors in the Inertial Guidance System, down range and vertical velocities.

Post flight evaluation has indicated that the IGS errors were due to two sources: 1) an incorrect computer insertion for the X accelerometer scale factor and bias compensation, and 2) a defective Y gyro.

Corrective action to preclude a re-occurrence of the S/C #3 problem has been taken. The accelerometer loops, which have been modified effective S/C #4 and up, provide improved stability so that there will be no variation out of the specified tolerance in the accelerometer parameters. Special gyro tests will be performed to insure that any units evidencing the S/C #3 Y gyro defect are detected prior to launch.

2.0 INTRODUCTION:

This report describes the analysis and testing efforts that were performed in isolating and correcting the causes of the anomalies that were observed in Inertial Guidance System performance during the ascent phase of the GT-2 and GT-3 missions. The description of the GT-2 and GT-3 tasks are discussed separately, except in those instances where it is necessary to discuss the investigations jointly.

2.1 GT-2 Anomaly:- The GT-2 anomaly was evidenced as an out-of-tolerance velocity error along the down-range (X) axis. Compared with MISTRAM and the GE/Burroughs radar data, the Inertial Measurement Unit (IMU) gained approximately 20 feet per second near booster engine cutoff (BECO) and 48 feet per second near sustainer engine cut-off for a total velocity error of 68 feet per second. The observed discontinuities in velocity measurements occurred at an acceleration threshold of approximately 4.4 g. The velocity increase appeared to occur in large steps over several seconds at linear g levels above 4.4 g. Vibration was discounted as the cause of the abnormal operation since the spacecraft vibration levels were below 0.2 g RMS at both flight conditions. There was no evidence of any computer problem during the mission.

2.2 GT-3 Anomaly.- The Inertial Guidance System possessed a larger than expected navigational error during the GT-3 mission with the most significant error being in radial velocity and altitude. The Space Technology Laboratory (STL) comparison of the IGS and radar tracking data corroborated the existence of the navigational error. The STL

2.2 (Continued)

analysis was based on IMU accelerometer data which indicates that the source of the navigational error was within the IMU. The GT-3 post-mission analyses indicate that the IGS navigated to an inertial velocity 19.6 feet/second high, an altitude 9,600 feet high and a radial velocity 133 feet/second high. As a result of the radial velocity error and the attendant altitude error, the IGS computer determined that the vehicle should pitch down. Since the primary guidance system was controlling the launch vehicle, a positive pitch attitude error was determined by the IGS computer. The pitch attitude error reached its limited value (±6 degrees) at 290 seconds and remained limited through SSECO.

A known shift in the X-accelerometer bias value existed during the final stages of pre-flight checkout. The change in accelerometer bias was also indicated by evaluation of the accelerometer's operation during the orbit phase. After accounting for a bias error, the shape of the X-velocity error curve (Figure 1), particularly during Stage I, appeared to be proportional to the X-acceleration which is indicative of an error in accelerometer scale factor. An explanation of the X-velocity error could not be made on the basis of accelerometer bias and scale factor effects only. Furthermore, the X and Y (Figure 2) velocity errors appeared to be coupled for the time interval about 180 seconds which would be characteristic of a pitch gyro drift or pitch reference offset error. The only significant error that occurred

2.2 (Continued)

near the time of the sharp break in the error curves is the change in polarity of the Y-acceleration. The possibility of an error in the Y accelerometer scale factor was discounted due to the shape of the Y-velocity error curve and its relation to the Y acceleration.

3.0 TEST PLAN.-

The test plans that were followed during the GT-2 and GT-3 anomaly investigations are described in the following paragraphs. The test plans were designed to isolate the cause of the problem, establish a design fix and/or screening tests to find other faulty units, and to verify that any design modification satisfied system requirements.

3.1 GT-2 Investigation Plan.-

From the post-mission evaluations, the cause of the GT-2 anomaly was isolated to the IMU and, in particular, to the X-accelerometer. Consequently post-mission computer hardware tests were considered unnecessary. Figure (3) shows a block diagram of the GT-2 investigation plan. The computer software simulation activity used to validate the computer operation is also shown in Figure (3).

3.1.1 Post-Flight Physical Inspection.-

Severe salt water corrosion precluded use of some portions of the IMU, but the platform and all system electronics boards were salvaged for testing. A system electronics connector housing, the Gimbal Control Electronics, and Static Power Supply were not operational due either to salt water damage or other causes. Substitutes were used for the damaged units. This substitution did not have a significant effect upon the accelerometer loop characteristics, however. The computer also sustained salt water damage, but since no hardware tests were contemplated, the damage did not hinder the GT-2 investigation.

3.1.2 Digital Computer.- The digital computer investigation was limited to simulation efforts in verifying proper operation of the software program during the mission. This effort was effectively completed by the start of the IMU testing effort. As a matter of background, it should be pointed out that extensive simulation effort had been performed in the development of the software program. The development simulation effort was culminated by the Mission Verification Simulation (MVS) which provided a marriage of the computer hardware, operational program, simulated end-instruments, and a 7090 representation of the launch vehicle dynamics. The MVS testing had confirmed that the operational program was flightworthy. Reference (b) provides further assurance of the soundness of the operational program.

3.1.2.1 Verification of Flight Operation.- Accelerometer and platform gimbal angle data obtained from telemetry were used to reconstruct the IGS navigational and steering parameters measured during the flight. The evaluations made use of two levels of simulation effort. One flight simulation program includes a FORTRAN model of the math flow equations using floating point arithmetic. The second simulation was an interpretive operational program simulation which executes the computer instructions with fixed point arithmetic and word length on the 7090.

3.1.3 Inertial Measurement Unit.-

3.1.3.1 Static Test Plan.-

3.1.3.1.1 Brief functional to verify operation subsequent to immersion.

3.1.3.1.2 Slip Ring Test.

3.1.3.1.3 Six orientation inertial parameter checks.

3.1.3.1.4 Accelerometer I.A. orthogonality measurements per TCL214 techniques.

3.1.3.1.5 Measure accelerometer pre-amp gains.

3.1.3.1.6 Critical internal visual inspection.

3.1.3.2 Centrifuge Test Plan

3.1.3.2.1 Centrifuge test with platform in inertial mode at initial gimbal angles of 180°, 0°, 25° for Gimbals 1, 3, and 4 respectively, per DAT procedure. Conduct tests with 2 minutes exposures at 3, 5, 7, and 9 g levels.

3.1.3.2.2 Centrifuge test with gimbals 1, 3, and 4 clamped at 0°, 0°, 25° respectively. The test shall be conducted with gradually increasing acceleration up to 9 g level. The test shall be conducted and instrumented to simulate and evaluate the X accelerometer flight performance.

3.1.3.2.3 Rerun 3.1.3.2.2 with Platform accelerometer pre-amp gains set at nominal value.

3.1.3.2.4 Other tests as required.

3.2 <u>GT-3 Investigation Plan</u>.- Post mission evaluations indicated that the causes of the GT-3 anomaly were IMU malfunctions. The Computer and IMU were returned to their respective vendors for testing. Figure 4 shows a block diagram of the GT-3 investigation plan.

3.2.1 <u>Post Flight Physical Inspection</u>.- All IMU units and the Computer experienced some salt water corrosion, but were operational.

3.2.2 <u>Digital Computer</u>.- Although the GT-3 abnormality was isolated to the IMU, tests were conducted on the computer hardware and software to establish that there was no computer abnormality masked by the IMU problem. As for all the software programs, extensive development simulation including Mission Verification Simulation had been performed prior to flight in establishing its flightworthy status.

3.2.2.1 <u>Verification of Flight Operation</u>.- The analysis was similar to the effort performed for GT-2. The flight accelerometer and platform gimbal angle data was used to reconstruct the IGS navigational and steering parameters measured during the flight. Both the operational program simulation and the FORTRAN simulation were used.

3.2.2.2 <u>Digital Computer Hardware Test Plan</u>.-

3.2.2.2.1 Visual Inspection.- Note major corrosion areas and any packaging anomalies.

3.2.2.2.2 Continuity Check.- Per IBM interface resistance measurement test procedure #63-385-1007.

3.2.2.2.3 Clean-up limited to minor wiping or compressed dry air removal of corrosion if necessary. Disassembly is not authorized.

3.2.2.2.4 Apply power and confirm that internal voltages, plus or minus 25 and plus 8, are in spec.

3.2.2.2.5 Verify memory per standard procedure. IGS ATP procedures 63-385-5000, Rev. E, Para. 3.3.1, 3.3.2, 3.3.5, and 3.3.6 shall be used to the extent possible. Record all updated constants and all errors.

3.2.2.2.6 If steps (1) thru (5) are accomplished successfully, load the diagnostic test program, defined by IBM listing and description #6444551 to 553. Connect the computer to acceptance test AGE, test program console, per IBM procedure #A63-385-0020 Rev. H. Operate the computer at least three hours with diagnostic program. Note any malfunction.

3.2.3 Inertial Measurement Unit Test Plan.-

3.2.3.1 Platform Tests using other than S/C #3 Equipment.-

3.2.3.1.1 Minimizing prior gimbal rotations, perform slip ring test.

3.2.3.1.2 Rotational interference test on all gimbals. Emphasis placed on pitch gimbal rotation in the vicinity of gimbals 1, 3, and 4 near 0, 0, and 90 degrees respectively. While this test is to be conducted in a 1 g field, consideration should be given to orienting the platform to simulate case position during the GT-3 flight time of 220-260 seconds.

3.2.3.1.3 Pitch and roll axis gyro and loop stability checks. Ascertain if stray torquing currents were applied to gyros and if stabilization loops were intermittent.

3.2.3.1.4 Gyro drift measurements per R-ED 21101, Rev. E.

3.2.3.1 IMU Tests using all operable Spacecraft 3 Equipment.-

3.2.3.2.1 Repeat Paragraph 3.2.3.1.3 at system level.

3.2.3.2.2 Malfunction detection system checks. Specifically determine operating limit of attitude M.D.S. versus gimbal hang-off.

3.2.3.2.3 IMU mode tests. Critically loop for any orbit rate anomalies.

3.2.3.2.4 Inertial component parameters. In addition to the standard test, gyros and accelerometers shall be evaluated regarding sensitivity to reversed gravity effects and cw/ccw orientation.

3.2.3.2.5 Dynamic response, threshold and SEF gyrocompass (0°, 0°, 0°) from angles of -5 degrees, plus 10 degrees and plus 16.5 degrees for pitch, yaw and roll. Record all gimbals response for 10 minutes minimum.

3.2.3.2.6 Abbreviated static accuracy.

3.2.3.2.7 Post cooldown checks.

4.0 TEST RESULTS.-

4.1 GT-2 Results.-

4.1.1 Digital Computer Software Investigation.-

4.1.1.1 Verification of Flight Operation.- No discrepancies were found in the operation of the flight computer or its outputs during the ascent portion of the mission. All in-flight attitude error data were duplicated to within 0.6 degree, velocity data within 0.5 feet per second and position data to within 60 feet.

4.1.2 Inertial Measurement Unit Investigation

4.1.2.1 Summary of Static Test Results.-

4.1.2.1.1 Slip Ring Tests.- The slip rings were tested to establish whether or not signal dropouts could have caused the velocity errors. These tests revealed no slip ring irregularities that could have caused velocity errors.

4.1.2.1.2 Six Orientation Inertial Parameters.- Tests of the Platform Inertial Component Parameters are summarized in Table I. There were no unusual deviations or out of spec. conditions.

4.1.2.1.3 Accelerometer IA Orthogonality Measurements.- Accelerometer orthogonality checks revealed no significant parameter shifts. This data is summarized in Table I.

4.1.2.1.4 Pre-Amp Gains Check.- Measurements were made to determine gains of S/C #2 accelerometer pre-amps. On the basis of a nominal gain of 1.8 volts per milliradian the S/C #2 gains were as follows:

X +18 percent above nominal

Y +13 percent above nominal

Z +13 percent above nominal

The gains were expected to be high due to a procedural error at the Vendor. However, the Vendor's analysis indicated that the effects of this error on the GT-2 flight would be minimal, and insufficient time was available to make the correction prior to the GT-2 launch. Later centrifuge test results showed that the velocity error might have been approximately 10 ft./sec. instead of the actual 68 ft./sec. had these gains been correct.

4.1.2.2 Centrifuge Tests.-

4.1.2.2.1 Centrifuge Test With Inertially Stable Platform.- Centrifuge tests with an inertially stabilized element (sinusoidal g inputs) indicated that the S/C #2 IMU behaved in a manner very similar to that of the DAT #2 system with 50% high gains. This data is summarized in Table II.

4.1.2.2.2 Centrifuge Tests With Clamped Gimbals.-

4.1.2.2.2.1 These centrifuge tests were conducted using the actual hardware and S/C #2 gain settings. The gimbals were clamped so as to provide a linear g input to the accelerometer loops. Linear

4.1.2.2.2.1 (Continued)

accelerations of from 3 to 9 g's were imposed on the loop to establish (1) whether or not the lock-up occurred during the linear g conditions, (2) how frequently the lock-up occurred, and (3) how much velocity was lost in a typical occurrence. Tests were also run at nominal preamp gains and at reduced gains to establish the effects of reduction in gain upon velocity insertion error.

4.1.2.2.2.2 Magnetic tape recording of the accelerometer pre-amp signals and the delta-V pulses allowed evaluation of the actual behavior patterns of the pulse rebalance circuits. Table III summarizes the results of the tests with S/C #2 flight gains. Approximately two minute runs were made at each g level indicated. Data was recorded between g levels on a ramp basis to determine if an increasing g level had a significant effect upon the results. This data indicates that increasing g level in itself has no significant effect. The steady state g level is the significant parameter affecting pulse lock-up.

To determine velocity gained per occurrence, a typical occurrence was plotted at each g level (Reference Figure 5). These curves were used in conjunction with the acceleration versus time curve of the actual Gemini flight. The average g level over a finite period of time versus feet per second loss at that level was used to predict velocity loss in that time

4.1.2.2.2.2 (Continued)

interval. Time intervals were integrated over the time of the flight at the g levels experienced in flight. The results are tabulated in Table IV.

Table IV indicates a total velocity error of 9.0 feet per second at booster engine cut-off, for a total of 64.7 feet per second. This compares with 20 and 48 feet per second for a total of 68 feet per second experienced in S/C #2 flight. The greater flight error at BECO may have been caused by a lock-up occurring at the time of BECO. At zero g's a positive pulse lock-up of a specific time duration will result in a significantly greater velocity error than at positive 5 g's. At zero g's the pendulum is driven toward the stop at 10.5 g's net input; at 5 g's the pendulum is driven to the stop with a net of 5.5 g's. Thus the velocity gained at the instant of BECO would be greater than that of an occurrence under linear g's. There is no apparent way to confirm a flight occurrence at BECO, however.

In summary, the centrifuge tests provided a remarkably close duplication of the S/C #2 errors.

4.1.2.2.3 <u>Other Centrifuge Tests</u>.- Tests conducted at both S/C #2 gains and at reduced gains in the <u>negative</u> acceleration direction indicated that the occurrence of torquer pulse hang-up was not of

4.1.2.2.3 (Continued)

sufficient duration to enable the pendulum to hit its stop. No velocity errors resulted from negative accelerations during the centrifuge runs. This is attributed to the non-symmetrical behavior of the rate network.

This implies that during flight, negative X acceleration did not cause velocity error. Had the accelerometer been turned around it is unlikely that any velocity error would have resulted from this effect during ascent.

Tests run in the positive acceleration direction at reduced gains resulted in significantly reduced errors. It is estimated that less than 10 feet per second error due to this effect would have occurred had the gains been reduced in S/C #2 to the design nominal gains. Flight gains in S/C #2 were actually measured to be approximately 18 percent above nominal. Tests run at reduced gains (75 percent of nominal) showed basically the same effect as tests run at nominal gains. The 75 percent gain tests showed an increased tendency for occurrences in the negative direction, however. A reduction in gains did not eliminate the pulse lock-up problem and was not considered to be a suitable corrective action for S/C #3.

4.1.3 Explanation of Pulse Lock-Up.- The situation which caused the velocity error in flight can be described as a condition of pulse polarity lockup wherein the torquer pulses to the accelerometer for a short

4.1.3 (Continued)

period of time (on the order of 40 milliseconds) do not respond to the polarity reversal commands from the accelerometer signal generator. Under certain conditions of linear g input a lock-up of pulses is of sufficient time duration to permit the pendulum to hit the physical stop within the accelerometer. Subsequent pulses do not produce pendulum motion and are therefore lost.

A typical occurrence of this phenomenon is shown in Figure 5. This is a plot of actual data taken during a 4.5 g centrifuge run. A positive pulse lock-up occurred for approximately 39 milliseconds. The loop recovered, but a net of approximately 14 delta-V's were gained.

This accelerometer loop problem has been attributed to the design of the Gemini rate network. This is shown schematically in Figure 6. The input to the rate network is a varying DC signal proportional to accelerometer pendulum position. It is limited by preceeding stage saturation to approximately 20 arc seconds of pendulum motion in either direction. The input maximum voltage under these conditions is approximately 2.5 volts. The output of the rate network goes to the level detector which sets the polarity of the digital logic in the succeeding pulse rebalance stages. The level detector has a threshold of ± 75 millivolts. The rate network output must pass through the 75 millivolt threshold in order to change the polarity of the rebalance pulses.

4.1.3 (Continued)

During high linear acceleration the nature of the rebalance circuit is such that the pendulum swings further and spends more time on one side of the null point than the other. Because of this, the lag capacitors (47 uf) in the rate network accumulate a charge over a period of time. The voltage on the capacitor eventually reaches a point where the demands from the signal generator of opposite polarity are not sufficient to overcome the effects of the charge on the lag capacitor at the input to the second stage emitter follower. After the pendulum has moved completely past the 20 arc second saturation point, all rate input to the level detector is lost. The capacitor must then discharge to the negative dc threshold level before the pulse polarity will be reversed. After the capacitor has discharged, proper loop operation will again be obtained. Proper loop operation continues until the capacitor again charges to the point where pulse lock-up occurs.

Note that when the pulse lock-up occurs all torquer pulses are of the polarity tending to oppose the input acceleration to the pendulum. Those pulses which continue to feed in after the pendulum has reached its stops are the ones which cause the velocity error. Figure 5 shows a typical occurrence wherein a lock-up of 140 pulses occurs. Of these, approximately 14 pulses are sent to the accelerometer after the pendulum has hit the stops, resulting in a 1.4 foot per second error. Because of the lack of symmetry in the

4.1.3 (Continued)

rate network, the torquer pulse lock-up is greater in the positive g input direction than in the negative g input direction. Centrifuge tests conducted with a negative acceleration applied to the accelerometer indicated that even though pulse lock-up did occur, it was not of sufficient time duration to cause velocity error.

4.2 <u>GT-3 Results</u>:

4.2.1 <u>Digital Computer Investigation</u>

4.2.1.1 <u>Verification of Flight Operation</u>.- The simulation results indicated that there were no discrepancies in the operation of the digital computer or its output during the Ascent portion of the mission. The position and velocity data obtained during the flight was reconstructed to within 200 feet and .4 foot per second. Behavior of the IGS attitude error signals was duplicated to within .2 degree. The limited IGS error signal following 290 seconds is attributed to the IMU anomaly. The post-flight reconstruction effort is documented in Reference (c).

4.2.1.2 <u>Digital Computer Hardware Test Results</u>.- The computer from S/C 3 was subjected to the tests of Paragraph 3.2.2.2 and no discrepancies were observed.

4.2.2 Inertial Measurement Unit Investigation

4.2.2.1 The results of the tests performed per the test plan of Paragraph 3.2.3 indicated that there were no significant IMU anomalies except as outlined in the following paragraphs.

4.2.2.2 X Accelerometer Anomaly.- Tests on the X accelerometer in the S/C #3 platform verified it as a significant contributor to the longitudinal velocity error. A history of the X accelerometer scale factor and bias measurements are presented in Figure 7. A portion of the shifts noted on Figure 7 can be attributed to differences in cabling between Honeywell and the Cape; however, some variance is due to instability in the X accelerometer pulse rebalance loop. Tests at the vendor verified the instability. This loop was modified to correct an acceleration sensitive error noted during GT-2 flight. After incorporation of the modifications for GT-3, further refinements were included effective S/C #4 and up. The latest accelerometer loop modification has eliminated the GT-3 stability problems.

4.2.2.3 Y Gyro Anomaly.- As noted on Figure 1, some residual longitudinal velocity error was attributed to a possible pitch attitude error. An investigation was conducted to determine the cause of this pitch attitude error. During standard ATP orientation checks the Y gyro, S/N H-11, which controls the pitch axis, indicated an erroneous and erratic acceleration sensitivity. When testing the

4.2.2.3 (Continued)

gyro in a normal orientation II configuration (output axis vertical up) shifts in the pre and post flight fixed torque drift were noted; changing the gyro to an O.A. down orientation gave fixed torque drifts which correlate well with pre-flight measurements. A history of the Y gyro drift measurements is included in Figure 8.

A simulation of the stage II pitch maneuver, by rotation through the earth's gravity field, was then performed. The polar plot, Figure 9, shows how the simulation was performed. The in-flight acceleration curve reflects application of combined flight accelerations as regards "g" level and angle relative to the Y gyro (times are seconds from lift-off). The test acceleration plot reflects application of the gravity field to the gyro with the rotation simulating flight acceleration vector angular rate. During this simulation, transient drift rates in the range of 80 to 150 times specification and of approximately one-half minute durations were observed. These values are of a magnitude comparable to those predicted by the analysis of the velocity error.

Additional substantiation that the Y gyro was a major contributor to the S/C #3 ascent problem is indicated in Figure 10. This plot indicates a predicted pitch attitude error reconstructed from the vertical velocity error during the Stage II flight and a typical pitch attitude error constructed using Y gyro drifts observed during the post flight simulation test. A comparison

4.2.2.3 (Continued)

of these plots indicates general agreement verifying that the pitch attitude error was caused by the defective Y gyro.

4.2.2.4 <u>S/C #3 Pitch Gyro (S/N H-11) Investigation Results</u>:

4.2.2.4.1 The gyro was returned to Honeywell, Minneapolis, where it was disassembled. When the dust cover was removed, fluorolube was found inside the cover and on the header pins. When the gyro was opened through the bellows seal, bubbles were found under the bellows area and as the gyro was tilted back and forth, other bubbles migrated from holes in the babble plate. The gyro was then drained and flushed with freon. No contamination was found other than that thought to be introduced by opening the device.

During this operation the main header seal which contained the leak had not been disturbed. The gyro was refilled, reassembled and tested satisfactory. The gyro was then submitted to three thermal cycles in an effort to re-admit air and reproduce the erroneous performance. Drift transients similar to, but of less magnitude than, those previously noted did occur.

The gyro was then drained and flushed, treated with dye-penetrant, about the leak area, potted inside and out, and dissected. Dye-penetrant was discovered on the inner and outer surfaces of the epoxy sealing groove in the area of the leak.

5.0 Corrective Action.-

5.1 GT-2 Anomaly:-

5.1.1 Corrective Action for S/C #3.- The X accelerometer loop in S/C #3 was modified by a redesigned rate network (Figure 11) which does not experience the pulse lock-up phenomenon. Centrifuge tests and threshold tests were conducted on the S/C #3 network with actual accelerometers. The results indicated basically the same performance as the unmodified networks except that there were no instances of pulse lock-up with the S/C #3 version.

The improved performance of the modified network is attributed to the addition of the six diode clamp circuit between the first and second stages of the rate network. This permits the second stage to follow the input within 1.8 volts and thus avoid the conditions resulting in pulse lock-up.

5.1.2 Corrective Action S/C #4 and Up.- As indicated in paragraph 4.2.2.2, the network described in Paragraph 5.1.1, caused the accelerometer bias and scale factor terms to be unstable. In addition there is a potential PRE loop turn-on problem. During the course of the PRE loop investigation it was found that the level detector output to the digital circuitry was lost when the level detector input signal exceeded 350 millivolts. This presented no problem during active loop operation but presented a possible problem when the loop was first turned on. If, at the instant of turn-on, the accelerometer pendulum was against the stop

5.1.2 (Continued)

and the digital logic called for a pulse polarity to drive it further into the stop, an excessive DC signal out of the rate network could block the level detector and thus prevent proper loop closure.

A final version of the rate network has been designed to eliminate the above problems. A schematic of this network is presented as Figure 12. This network has been incorporated in all pulse rebalance electronics, effective S/C #4 and up.

5.2 GT-3 Anomaly.

5.2.1 X Accelerometer Anomaly.- The accelerometer problem due to bias and scale factor instability has been corrected by incorporation of the latest accelerometer pulse rebalance loop compensation network. It is anticipated that insertion of the latest accelerometer parameters in the computer will eliminate accelerometer problems on future flights.

5.2.2 Pitch Gyro Anomaly.- No conclusive corrective action can be stipulated for the leaking gyro. However it is recommended that a test or tests be performed at Honeywell during PDA and at the Cape prior to launch in an attempt to detect other gyros that experience this problem. Due to the transitory nature of the

5.2.2 (Continued)

gyro drift rates, a special test utilizing rapid rotation through an acceleration field is required to test for the condition. Tests performed on the X and Z gyros in the S/C #3 platform and on all gyros in the S/C #2 platform indicated the defective Y gyro was unique. The S/C #4 and S/C #5 platforms have been tested at MAC, St. Louis, and verified free from similar defective gyros; all other platforms will be verified at Honeywell prior to shipment and the S/C #5 and up will be tested at the Cape.

6.0 Conclusions.-

6.1 GT-2.- The results of the test program clearly indicate the cause of the velocity gain during ascent in the Gemini S/C #2 mission. The problem was duplicated with a centrifuge using the actual flight hardware. Corrective action has been implemented for all future systems to completely eliminate the torquer pulse lock-up phenomenon and thus prevent a recurrence of this error source on subsequent missions.

6.2 GT-3.- The results of the investigations into the GT-3 ascent anomaly indicate that the error was caused by: (1) incorrect X accelerometer scale factor and bias terms being inserted in the computer due to an instability of these parameters, and (2) a fluorolube leak in the pitch gyro that allowed a gas bubble to enter the gyro and migrate around the header assembly as a result of the change in acceleration vector along the output axis. The scale factor and bias instability has been corrected on future systems by incorporation of a redesigned pulse rebalance loop rate network. The exact reason for the pitch gyro localized lack of adhesion of the epoxy seal, which ultimately allowed the fluorolube to leak and admit gas, has not been determined. Special gyro tests will be performed on all future units to insure that any units evidencing the S/C #3 pitch gyro defect are detected prior to launch.

REFERENCES

(a) "Gemini Program GT-3 Mission Report", dated April 1965.

(b) "Validation of Gemini IGS Computer Program and IGS Guidance Equations for Spacecraft GT-2" Aerospace Report TOR-469 (5126-41)-2, dated 10 November 1964.

(c) "Gemini GT-3, Ascent Post-Flight Analysis Report" IBM Report 3-260-6096, dated 9 April 1965.

(d) MAC Report B624, "Verification of Gemini Spacecraft #2 Ascent Velocity Error".

TABLE I

RESULTS FOR THE GEMINI SYSTEM PERFORMANCE PARAMETER
EVALUATION OF IMU SYSTEM FOR SPACECRAFT 2

Dates Data Taken: 13 February 1965

Comments: Platform S/N H-13, System Electronics S/N H-12, Static Power Supply S/N H-8, Gimbal Control Electronics S/N G-5

Component Serial Numbers		
	X Gyro B17/G-3	X Accel. H-60
	Y Gyro H-45	Y Accel. H-62
	Z Gyro H1/G-3	Z Accel. H-76

Gyro Parameters

Gravity Insensitive Drift	Units = deg./hr.
Spec. Tolerance Range	
X Gyro (RX)	1.46
Y Gyro (RY)	0.44
Z Gyro (RZ)	-0.11

Mass Unbalance Drift	Units = deg./hr./g
Spec. Tolerance Range	±0.5
X Gyro MUSRA	0.13
Y Gyro MUSRA	-0.41
Z Gyro MUSRA	-0.38
X Gyro MUIA	-0.48
Y Gyro MUIA	0.33
Z Gyro MUIA	-0.01

Accelerometer Parameters

Bias	Units = 0.001 g
Spec. Tolerance Range	±10.0
X Accel. (BX)	-1.17
Y Accel. (BY)	1.08
Z Accel. (BZ)	1.70

Scale Factor — Units = ft./sec./pulse

TABLE I (Continued)

Spec. Tolerance Range	0.086 to 0.110
X Accel. (SFX)	0.093691
Y Accel. (SFY)	0.0963005
Z Accel. (SFZ)	0.096097
Misalignment between the Accel. Input Axes	Units = Arc Seconds
X and Y Accel.	-32.3
Y and Z Accel.	105.1
X and Z Accel.	102.0
Misalignment between Accel. Input Axis and Cube Face	
X Accel. in XY Plane	53.2
X Accel. in XZ Plane	25.4
Y Accel. in XY Plane	19.3
Y Accel. in YZ Plane	198.4
Z Accel. in ZX Plane	76.6
Z Accel. in ZY Plane	96.1
Misalignment between Accel. Input Axis and Case Axis	
Spec Tolerance Range	$\pm$300.0
X Accel. to Case Axis in XY	-9.2
X Accel. to Case Axis in XZ	37.5
Y Accel. to Case Axis in YX	-24.7
Y Accel. to Case Axis in YZ	243.5
Z Accel. to Case Axis in ZX	64.5
Z Accel. to Case Axis in ZY	-141.1

TABLE II

COMPARISON OF SINUSOIDAL G ACCELERATION OF SPACECRAFT 2 AND DAT NO. 2 HARDWARE

This data represents accumulated ΔV's over approximately a 30 second period of time. The counters were synchronized with the centrifuge arm to eliminate position errors.

SPACECRAFT 2 DATA

X Accelerometer (18% high gains)

Run	3g	4g	5g	6g	7g	8g	9g
(1)	+2	+3	+5	+5	+100	+329	+1287
(2)	+5	+2	+2	+27	+42	+412	+768
(3)	+1	+2	+3	+29	+64	+301	+1036
(4)	0	+3	+5	+6	+80	+366	+1800
* P/A Sat	None	None	None	1/200	1/15	1/8	1/4

Z Accelerometer (13% high gains)

Run	3g	4g	5g	6g	7g	8g	9g
(1)	2	0	-1	+1	+26	+1317	+1753
(2)	2	0	0	+95	+332	+1350	+1674
(3)	1	0	-1	+71	+377	+1193	+1968
(4)	0	+1	-3	+36	+152	+1262	+1820
*P/A Sat	None	None	None	1/15	1/2	1/2	1/1

* Pre-amp saturation - number of occurrences/time interval in seconds.

DESIGN APPROVAL NO. 2 SYSTEM

X Accelerometer (60% high gains)

Run	4.5g	7.2g	9.0g	10.5g
(1)	+10	+72	+117	+2120
(2)	+ 9	+66	+213	+2143
(3)	+12	+47	+372	+1746
(4)	+ 6	+ 8	+194	+2206

TABLE II (Continued)

Z Accelerometer (47% High gains)

Run	4.5g	7.2g	9.0g	10.5g
(1)	-18	-34	+131	+510
(2)	-21	-32	+121	+469
(3)	-14	-31	+180	+362
(4)	-20	-28	+190	+452

DESIGN APPROVAL NO. 1 SYSTEM

X Accelerometer (nominal gains)

Run	4.5g	7.25g	9.0g	10.5g
(1)	+4	+8	+18	+31
(2)	+8	+13	+17	+32
(3)	+6	+10	+15	+28
(4)	+6	+10	+18	+26

Z Accelerometer (nominal gains)

Run	4.5g	7.25g	9.0g	10.5g
(1)	-8	-22	-40	-52
(2)	-8	-23	-41	-47
(3)	-4	-20	-37	-42
(4)	-4	-20	-30	-46

TABLE III

CENTRIFUGE TEST DATA

G Level (Nominal)	Number of Occurrences Per Second Average	Feet Per Second Velocity Gained Per Occurrence (Typical)	Feet Per Second Gained Per Second
POSITIVE ACCELERATION			
4.0	0	0	0
4.5	0.067	1.4	0.0950
5.0	0.567	1.8	1.021
5.5	1.188	3.1	3.683
6.0	1.917	1.5	2.876
7.0	2.417	1.0	2.417
8.0	2.833	0.9 (est)	0
9.0	3.600	0.8 (est)	0
NEGATIVE ACCELERATION			
4.0	0	0	0
5.0	0	0	0
6.0	0	0	0
7.0	0	0	0
8.0	0.05	0	0
9.0	2.6	0	0

TABLE IV

CENTRIFUGE TEST DATA SPACECRAFT 2

ORIGINAL FLIGHT HARDWARE

	"g" level (ft/sec^2)	Time (sec)	Time (sec)	Error (ft/sec/ sec)	Error ft/sec)	Error Corrected for .0936 Scale Factor
	143 to 150	146.2 to 148.6	2.4	.2	.48	
	150 to 160	148.6 to 151.8	3.2	.6	1.92	
BECO	160 to 170	151.8 to 154.3	2.5	1.55	3.88	
	170 to 175	154.3 to 155.4	1.1	3.0	3.3	

					9.58	9.0
	143 to 150	308.5 to 311.9	3.4	.2	.68	
	150 to 160	311.9 to 315.6	3.7	.6	2.22	
	160 to 170	315.6 to 319.3	3.7	1.55	5.74	
	170 to 180	319.3 to 322.6	3.3	3.35	11.06	
SECO	180 to 190	322.6 to 325.6	3.0	3.35	10.05	
	190 to 200	325.6 to 328.3	2.7	3.875	10.46	
	200 to 210	328.3 to 331.0	2.7	2.65	7.16	
	210 to 220	331.0 to 333.0	2.0	2.48	4.96	
	220 to 230	333.0 to 335.0	2.0	2.4	4.8	
	230 to 234	335.0 to 336.0	1.0	2.4	2.4	

					59.53	55.7

					69.11	64.7

GT-3
X AXIS ERROR SOURCES VS. TIME

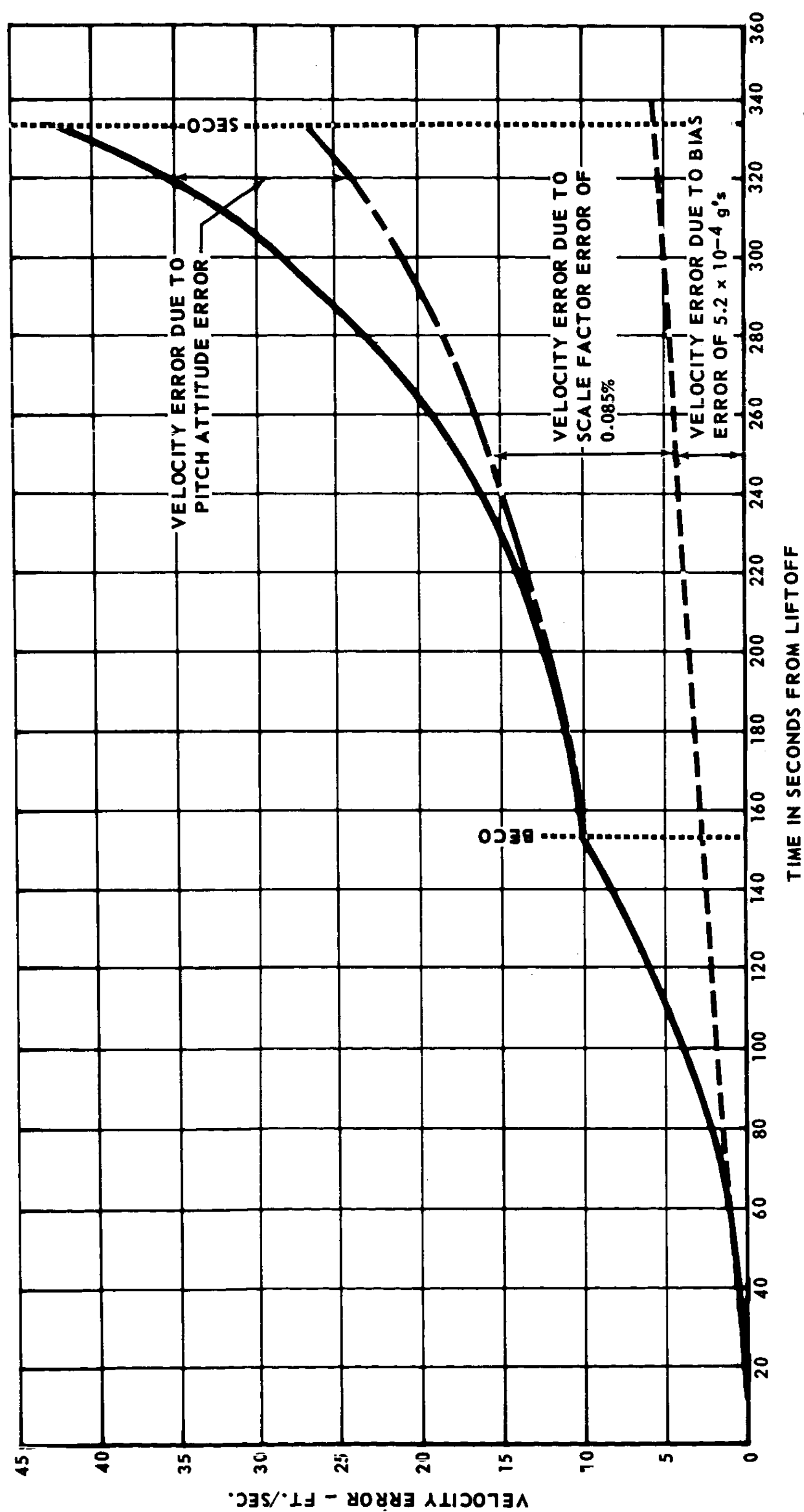


FIGURE 1

[redacted]

GT-3

COMPUTER Y AXIS VELOCITY ERROR VS. TIME

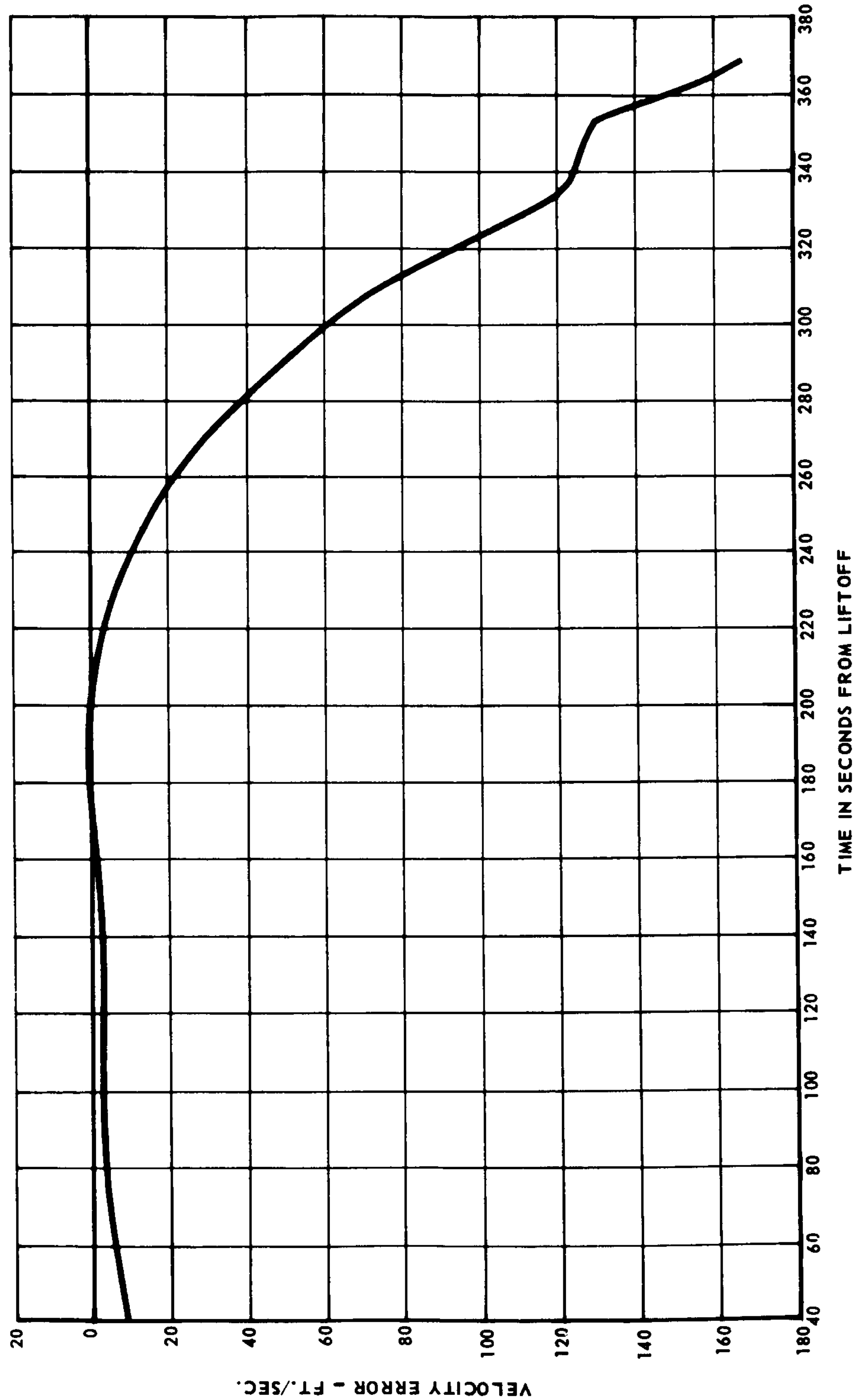


FIGURE 2

GT-2 ANOMALY INVESTIGATION PLAN

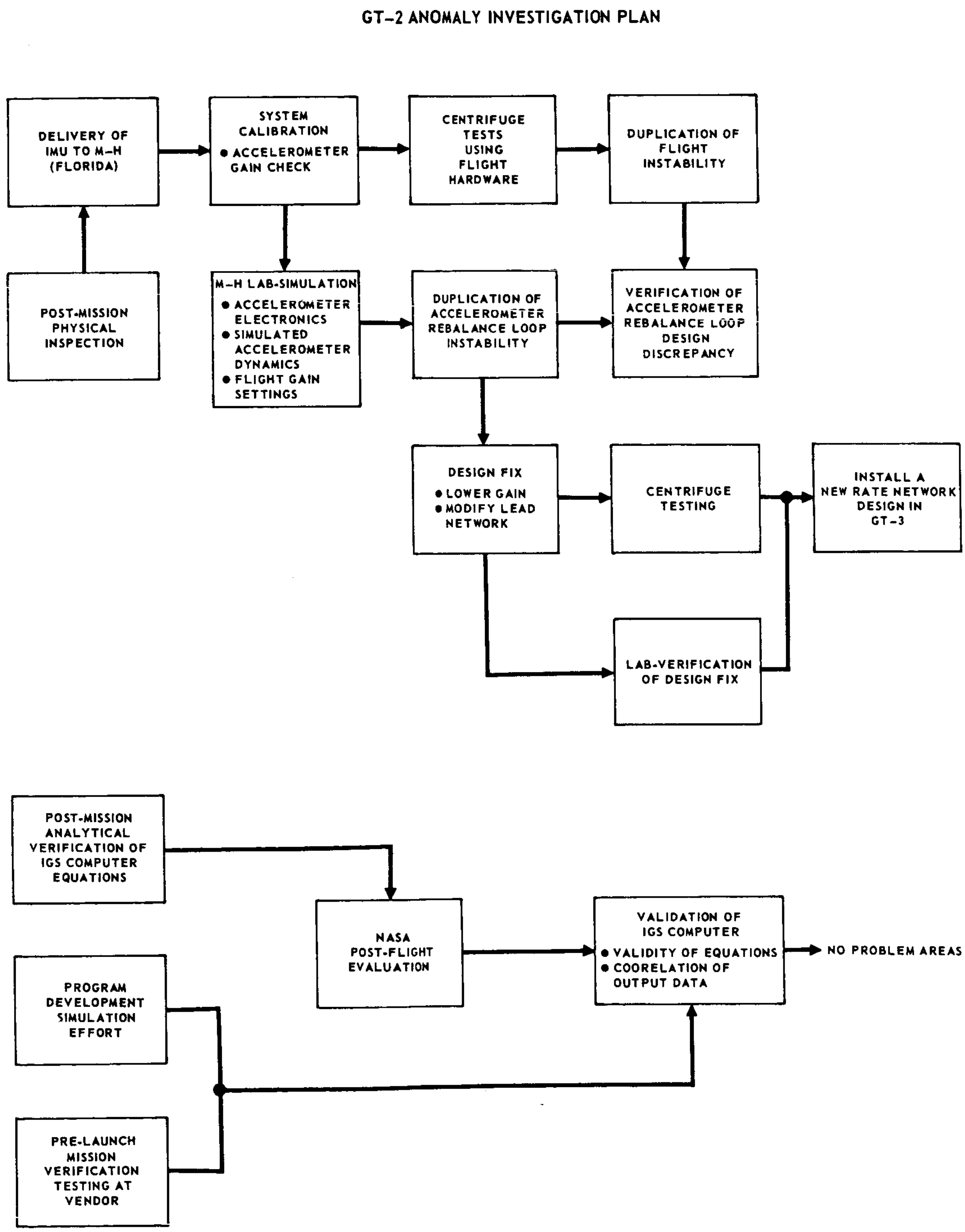


FIGURE 3

GT-3 ANOMALY INVESTIGATION PLAN

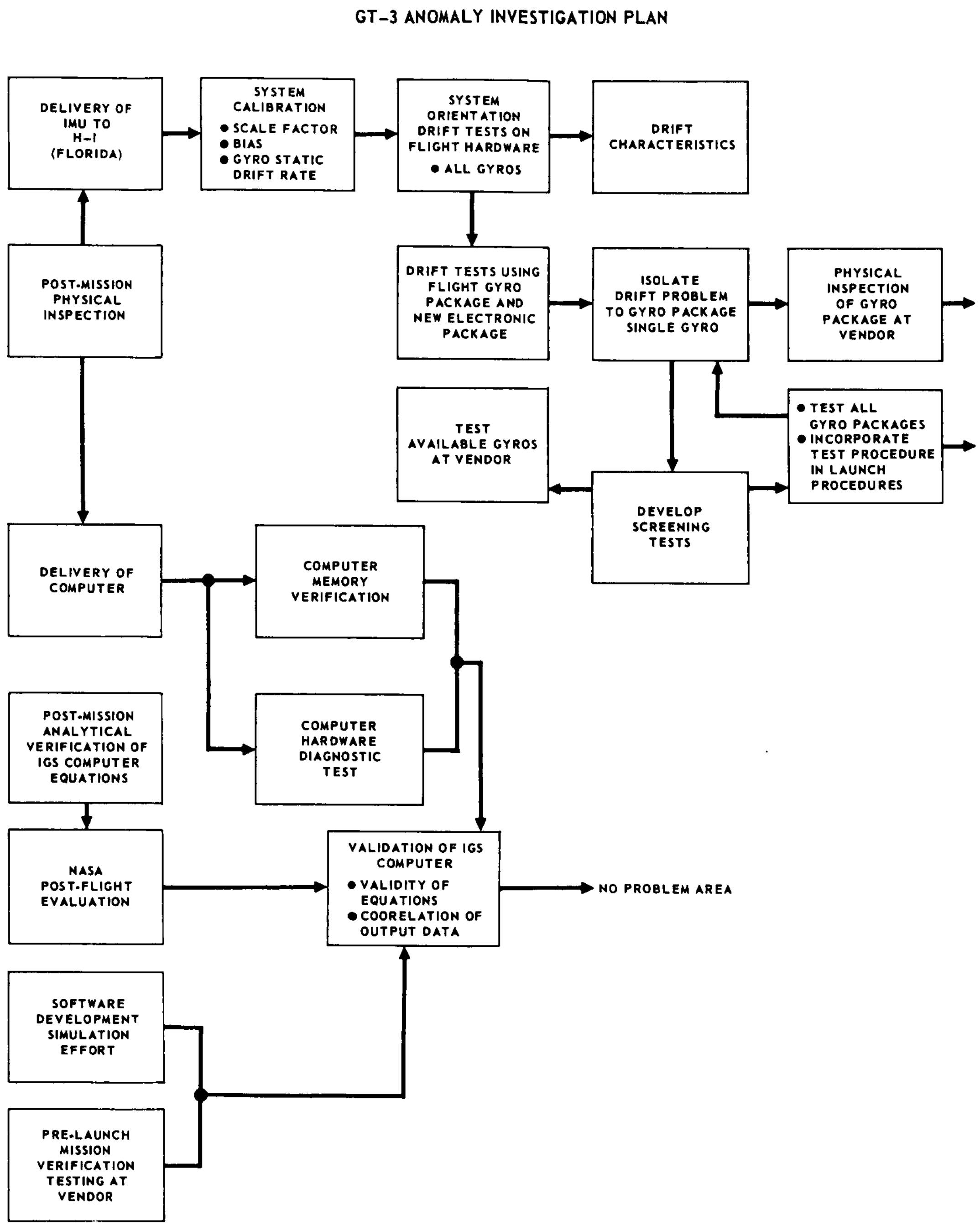


FIGURE 4

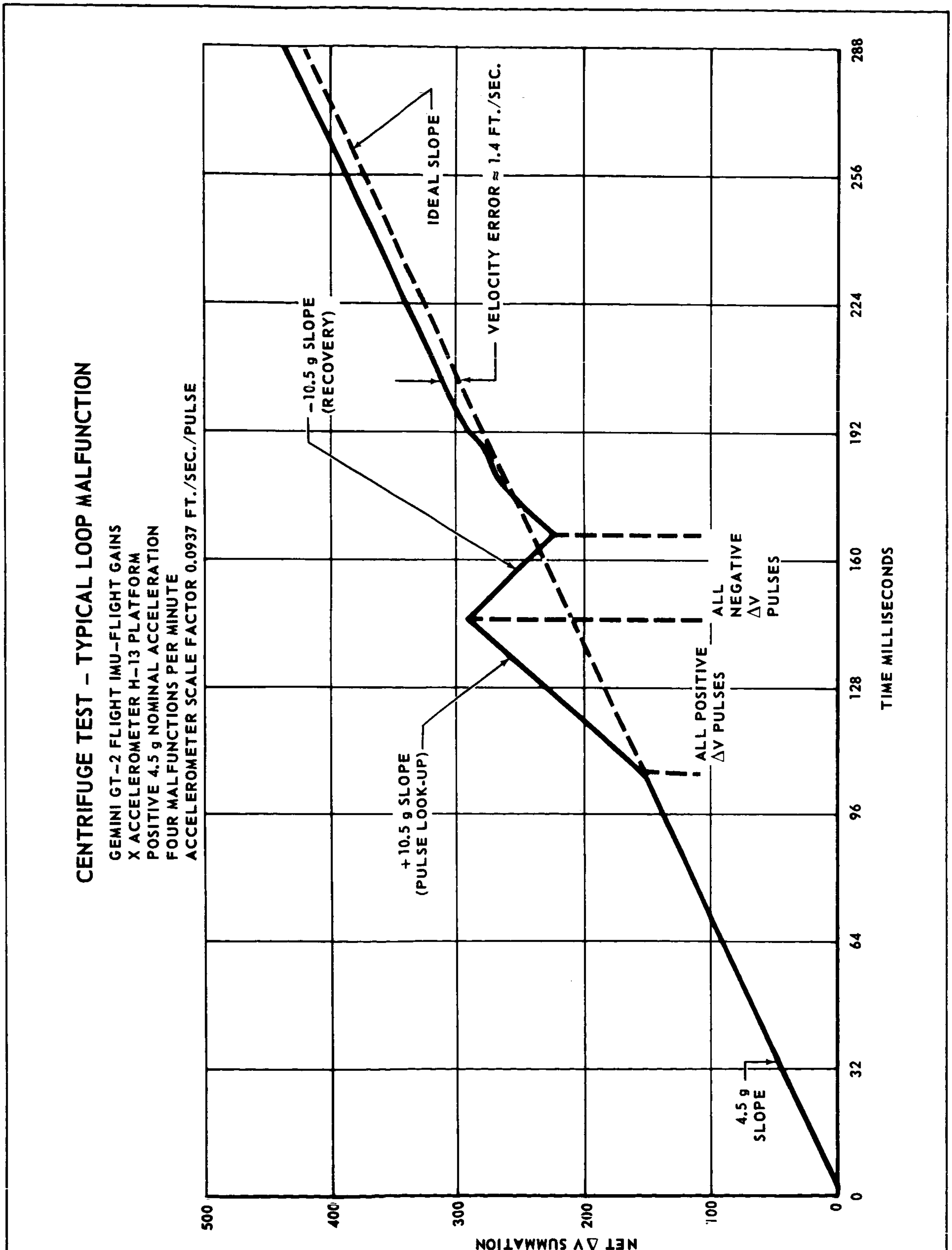

CENTRIFUGE TEST – TYPICAL LOOP MALFUNCTION
GEMINI GT-2 FLIGHT IMU-FLIGHT GAINS
X ACCELEROMETER H-13 PLATFORM
POSITIVE 4.5 g NOMINAL ACCELERATION
FOUR MALFUNCTIONS PER MINUTE
ACCELEROMETER SCALE FACTOR 0.0937 FT./SEC./PULSE
IDEAL SLOPE
VELOCITY ERROR ≈ 1.4 FT./SEC.
−10.5 g SLOPE
(RECOVERY)
+10.5 g SLOPE
(PULSE LOOK-UP)
ALL NEGATIVE
ΔV
PULSES
ALL POSITIVE
ΔV PULSES
4.5 g
SLOPE
0
32
64
96
128
160
192
224
256
288
TIME MILLISECONDS
0
100
200
300
400
500
NET ΔV SUMMATION

FIGURE 5

SPACECRAFT 2 RATE NETWORK

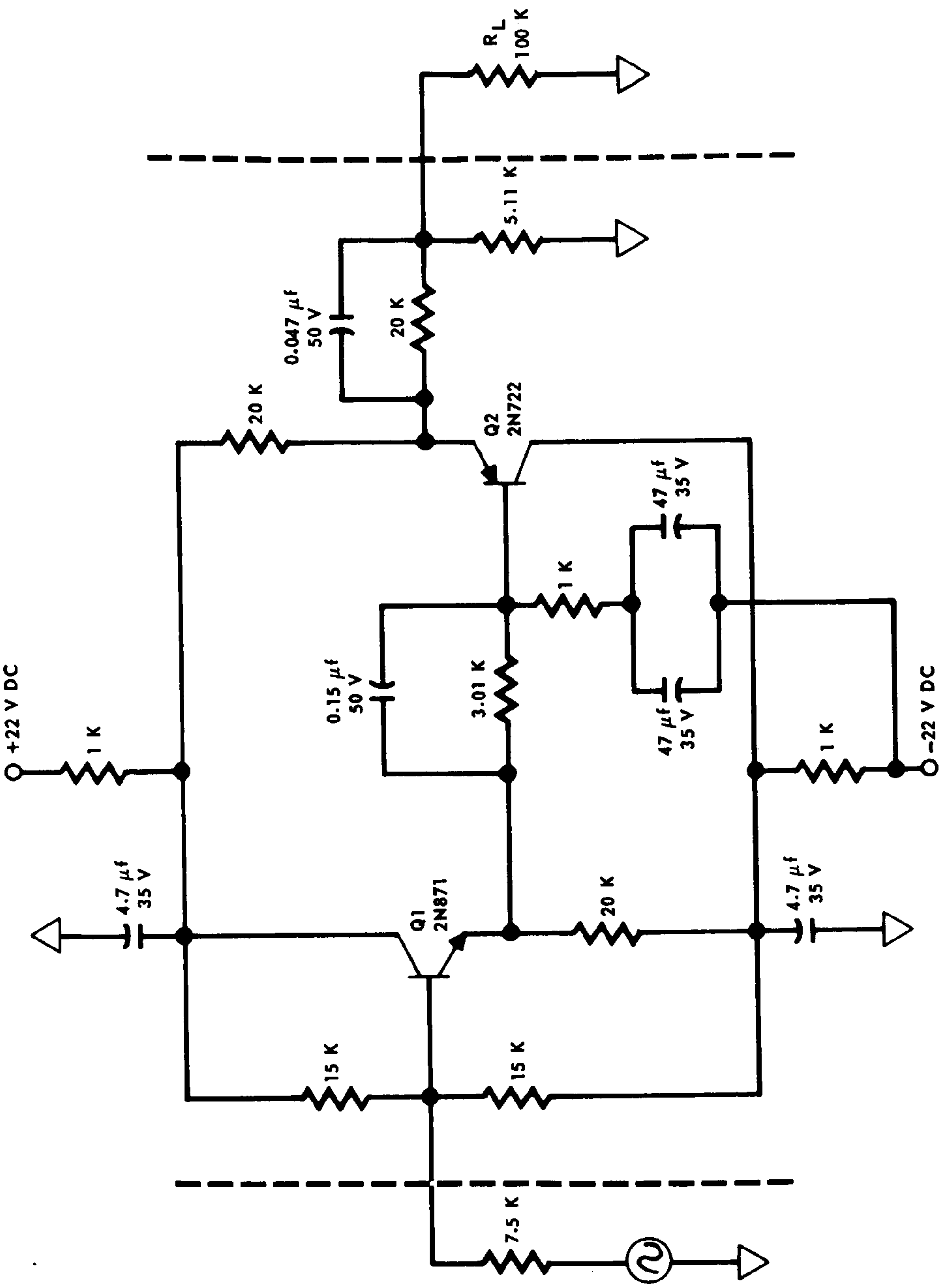


FIGURE 6

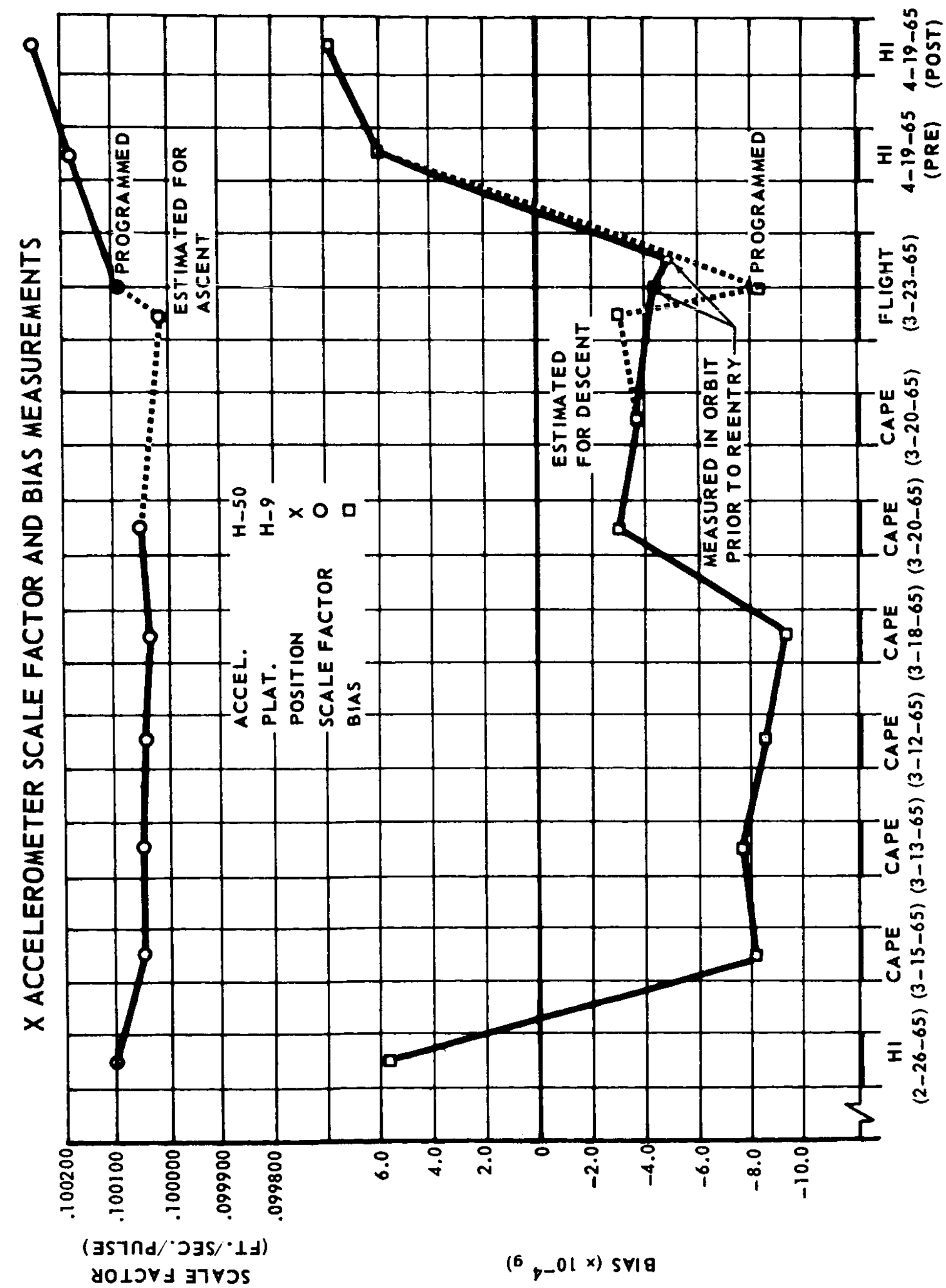
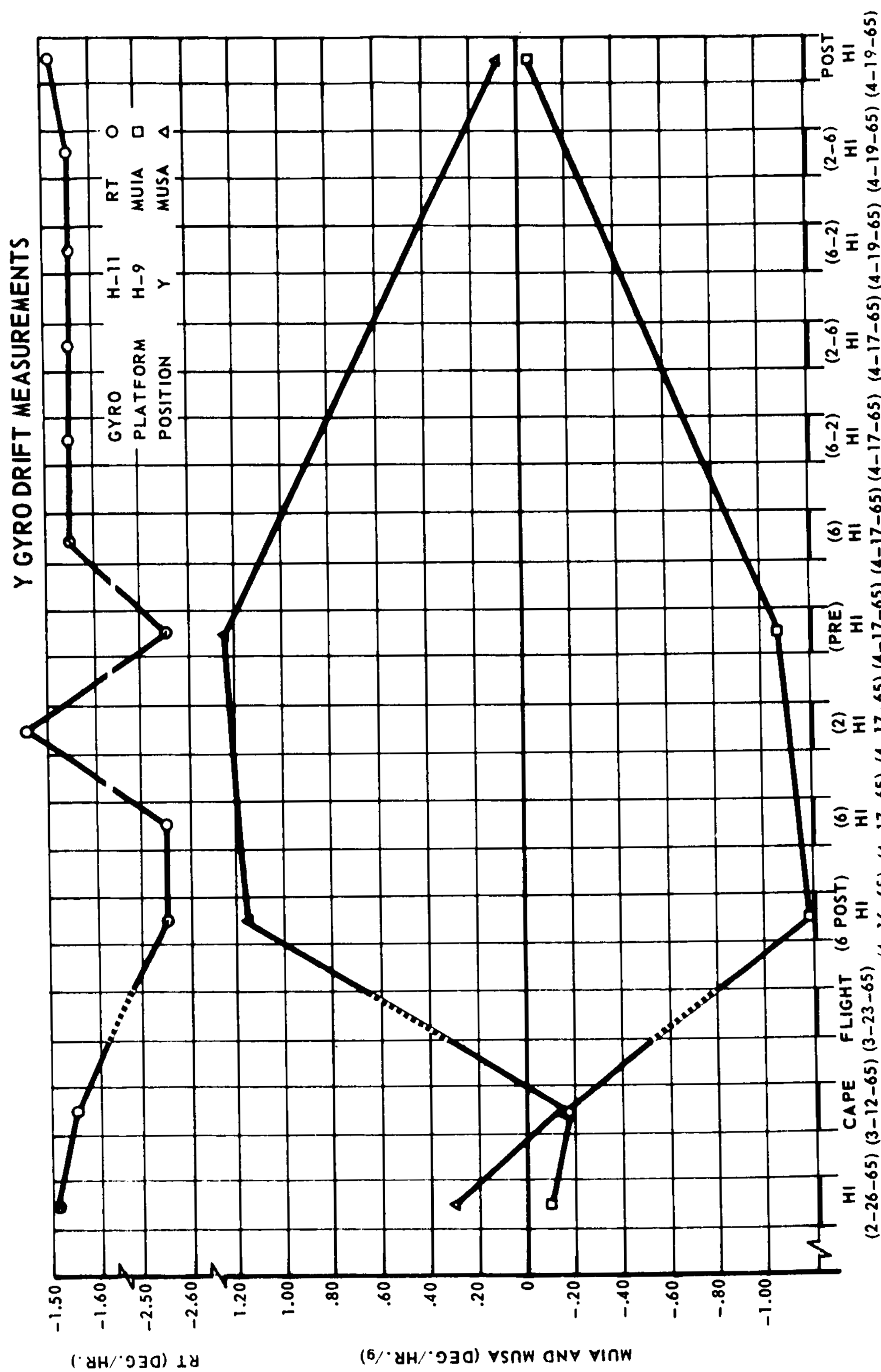
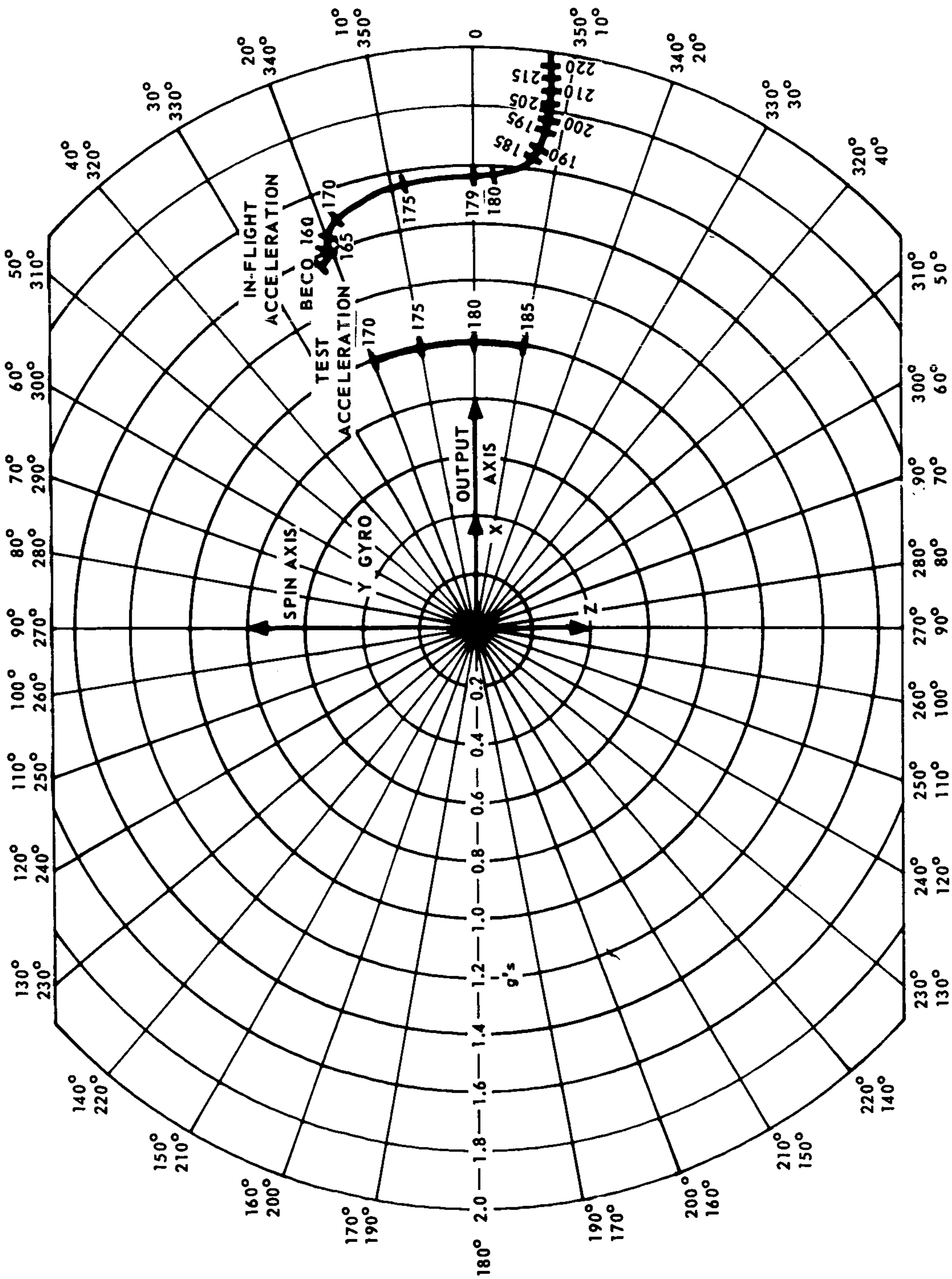

X ACCELEROMETER SCALE FACTOR AND BIAS MEASUREMENTS
PROGRAMMED
ESTIMATED FOR ASCENT
ESTIMATED FOR DESCENT
MEASURED IN ORBIT PRIOR TO REENTRY
PROGRAMMED
ACCEL. H-50
PLAT. H-9
POSITION X
SCALE FACTOR O
BIAS □
.100200
.100100
.100000
.099900
.099800
SCALE FACTOR (FT./SEC./PULSE)
6.0
4.0
2.0
0
-2.0
-4.0
-6.0
-8.0
-10.0
BIAS (x 10^-4 g)
HI (2-26-65)
CAPE (3-15-65)
CAPE (3-13-65)
CAPE (3-12-65)
CAPE (3-18-65)
CAPE (3-20-65)
CAPE (3-20-65)
FLIGHT (3-23-65)
HI 4-19-65 (PRE)
HI 4-19-65 (POST)

FIGURE 7



Y GYRO DRIFT MEASUREMENTS
GYRO H-11 RT ○
PLATFORM H-9 MUIA □
POSITION Y MUSA △
RT (DEG./HR.)
MUIA AND MUSA (DEG./HR./g)
-1.50
-1.60
-2.50
-2.60
1.20
1.00
.80
.60
.40
.20
0
-.20
-.40
-.60
-.80
-1.00
HI (2-26-65)
CAPE (3-12-65)
FLIGHT (3-23-65)
(6 POST) HI (4-16-65)
(6) HI (4-17-65)
(2) HI (4-17-65)
(PRE) HI (4-17-65)
(6) HI (4-17-65)
(6-2) HI (4-17-65)
(2-6) HI (4-17-65)
(6-2) HI (4-19-65)
(2-6) HI (4-19-65)
POST HI (4-19-65)

FIGURE 8



ACCELERATION PROFILES ON Y GYRO

FIGURE 9

GT-3
PITCH ATTITUDE ERROR VS. TIME

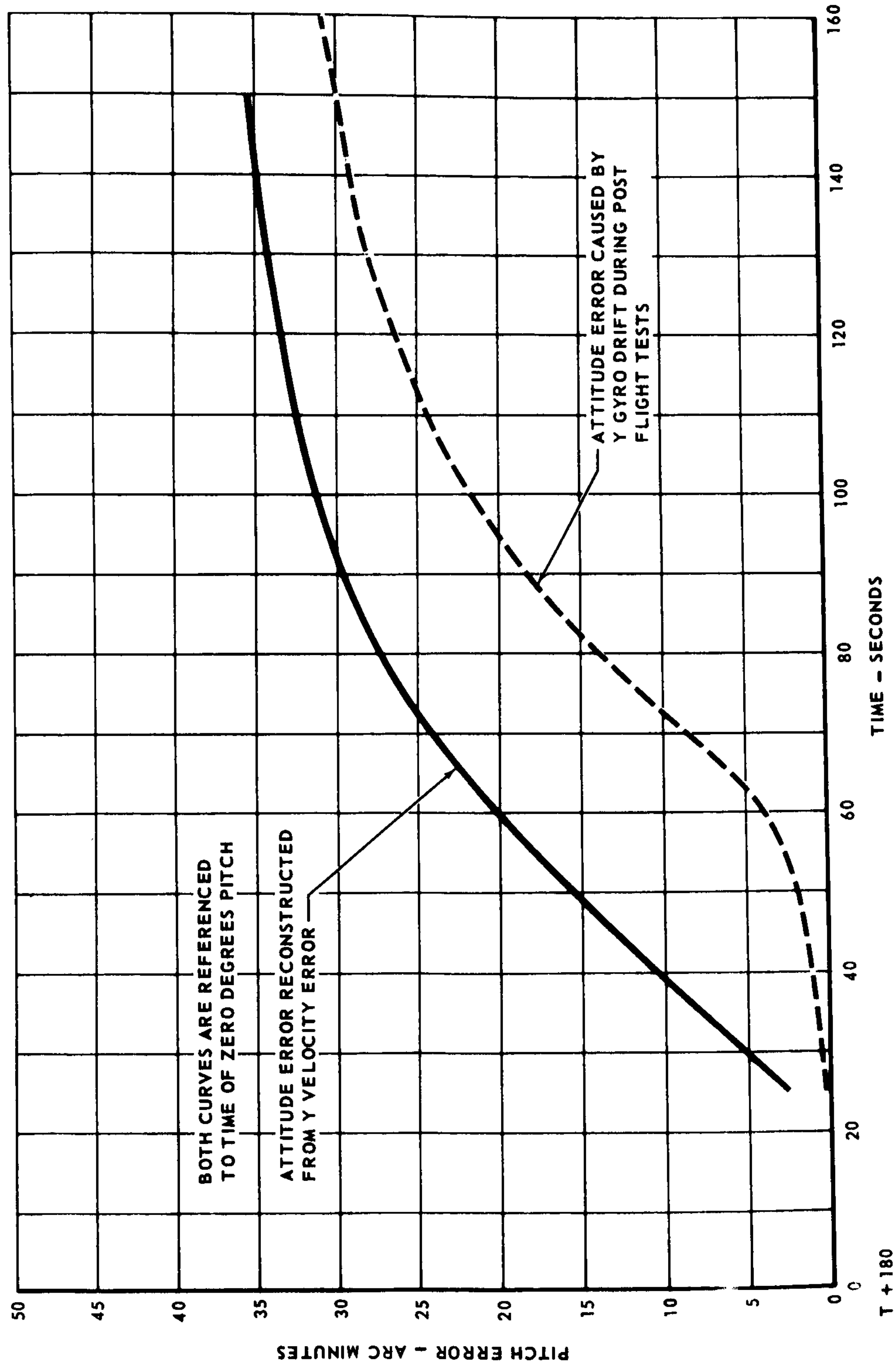
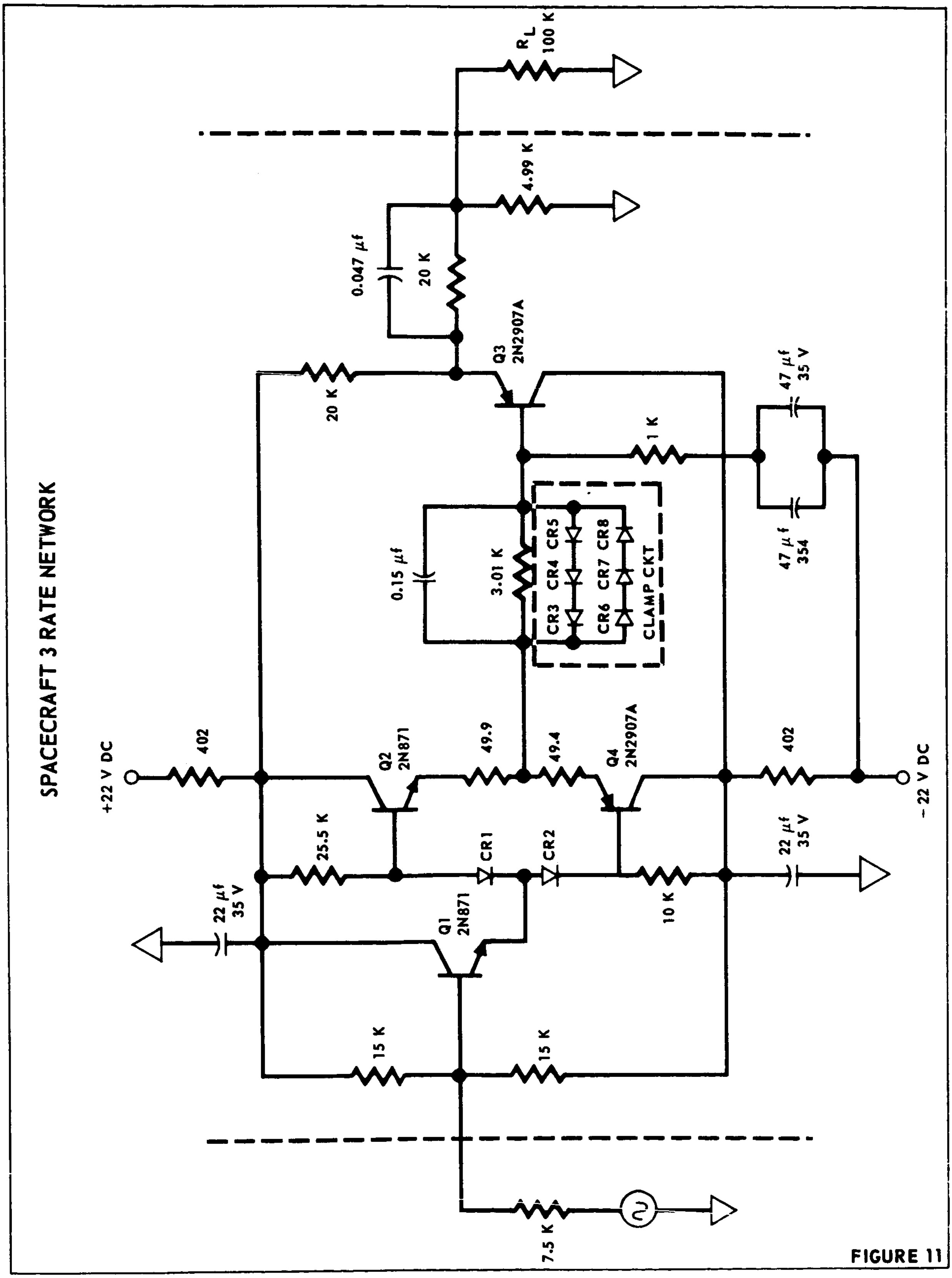


FIGURE 10



SPACECRAFT 3 RATE NETWORK

FIGURE 11

FINAL RATE NETWORK S/C-4 AND UP

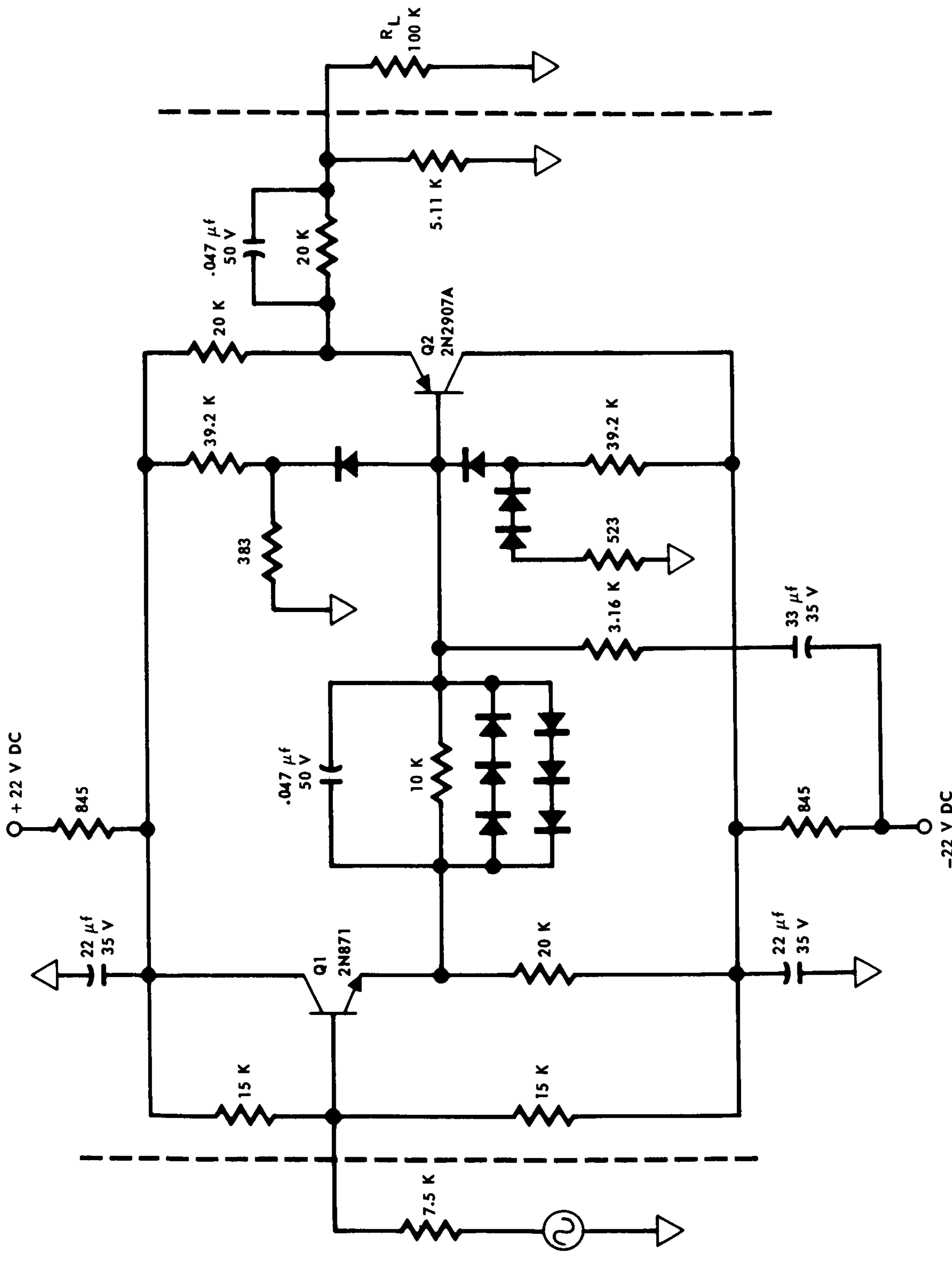


FIGURE 12